

Millimeter-wave GaN-based HEMT development at ETH-Zürich

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We review the AlGaIn/GaN high electron mobility transistor (HEMT) activities in the Millimeter-Wave Electronics Group at ETH-Zürich. Our group's main thrust in the AlGaIn/GaN arena is the extension of device bandwidth to higher frequency bands. We demonstrated surprising performances for AlGaIn/GaN HEMTs grown on high-resistivity (HR) silicon (111) substrates, and extended cutoff frequencies of 100 nm gate devices well into the millimeter (mm)-wave domain. Our results narrow the performance gap between GaN-on-SiC (or sapphire) and GaN-on-silicon and establish GaN-on-Si as a viable technology for low-cost mm-wave electronics. We here contrast the difference in behaviors observed in our laboratory between nominally identical devices built on high-resistivity silicon (HR-Si) and on sapphire substrates; we show high-speed devices with high-cutoff frequencies and breakdown voltages which combine $f_{T,MAX} \times BV$ products as high as 5–10 THz V, and show AlGaIn/GaN HEMTs with f_T values exceeding 100 GHz on HR-Si. Although the bulk of our activities have so far focused on AlGaIn/GaN HEMTs on HR-Si, our process produces excellent device performances when applied to GaN HEMTs on SiC as well: 100 nm gate transistors with $f_T > 125$ GHz have been realized at ETH-Zürich.

Keywords: AlGaIn/GaN, GaN-on-Si, HEMT, Millimeter-wave electronics

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I. INTRODUCTION

The present article highlights some of the AlGaIn/GaN high electron mobility transistor (HEMT) activities of the recently established Millimeter-wave Electronics Laboratory at ETH-Zürich. The Group was launched in 2006 with the mandate to develop better, higher performance heterostructure devices, principally for future telecommunication systems. Our three principal areas of interest are double heterojunction bipolar transistors (DHBTs) based on the InP/GaAsSb heterostructure system, InP HEMTs for low-noise applications, and GaN-based HEMTs, which are the focus of the present article. The fundamental philosophy underlying our AlGaIn/GaN HEMT activities involves leveraging the ETH InP monolithically integrated circuit (MMIC) process capability to develop a GaN-based MMIC mm-wave platform.

Because of their now well-appreciated set of physical properties, GaN-based HEMTs remain the focus of intense interest for high-power, wideband, and/or high-temperature applications [1, 2]. The key benefits of the (Al,Ga)N/GaN material system for microwave and mm-wave HEMTs are of course associated with their wide energy gaps and the high two DEG-channel charge densities resulting from the spontaneous and piezoelectric polarizations associated with the lattice mismatch between (Al,Ga)N and GaN. In principle, this combination of characteristics makes possible rugged high-current drive wideband transistors capable of operating at high voltages and temperatures.

The highest speed GaN HEMTs have historically been implemented on sapphire or on SiC substrates. Because of their affordability, ample supply, and good thermal conductivity at operating junction temperatures, high-resistivity silicon (HR-Si) substrates provide a low-cost solution for the realization of GaN-based power transistors in the lower microwave frequency bands. Our group does not have a particular preference for any given substrate technology: historically, we have published results for devices grown on sapphire and SiC. More recently, since re-locating to ETH-Zürich, our work involved devices on HR-Si substrates because of a good relation with a supplier of epitaxial layers. As a result, our recent work established that GaN-based HEMTs grown on HR-Si also offer very good performances at mm-wave frequencies [3, 4], culminating with the realization of 100 nm gate (Al,In)N/GaN HEMTs on HR-Si with cutoff frequencies as high as $f_T = 102$ GHz for AlInN/GaN HEMTs grown at EPFL [5]. We will later show that these successes also carry over to devices on SiC substrates. All transistors discussed in this paper were fabricated on MOCVD-grown epitaxial layers.

In Section II, we compare the behavior of similar AlGaIn/GaN HEMTs grown on HR-Si and sapphire substrates. We show that although the devices display similar DC and RF performances, they react differently to various factors such as the presence of passivation layers. As well, we demonstrate high-breakdown voltages with interesting cutoff frequencies in transistors with larger source-to-drain spacings. In Section III, we discuss some the work our group has carried out to extend the operating frequencies of AlGaIn/GaN HEMTs culminating with cutoff frequencies exceeding 100 and 125 GHz for devices respectively grown on HR-Si and SiC substrates.

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II. COMPARISON OF HEMTs ON HR-Si AND SAPPHIRE SUBSTRATES

AlGaIn/GaN heterostructures used for this study were MOCVD-grown on either (111) HR-Si or sapphire substrates. On HR-Si a 2 μm GaN buffer was used, followed by 18.5 nm of $\text{Al}_{0.27}\text{Ga}_{0.73}\text{N}$ and 2 nm GaN cap. A 2.9 μm GaN buffer was used on sapphire, followed by 25 nm of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ and a 2 nm GaN cap. The epitaxial layers are similar although not strictly identical, since they originate from different commercial vendors. Device processing details were given in [3]. The as-grown electron sheet densities and mobilities on HR-Si (sapphire) were, respectively, 8.5×10^{12} (1.1×10^{13})/ cm^2 and 1200 (1000) cm^2/Vs .

Circular transmission line measurement patterns reveal sheet and contact resistance values of 640 (550) $\Omega/\text{sq.}$ and 0.46 (0.55) $\Omega\cdot\text{mm}$ on the HR-Si (sapphire) substrate. DC characteristics were measured using an Agilent 4156A semiconductor parameter analyzer. Figure 1 superposes representative DC characteristics for $2 \times (0.1 \times 75) \mu\text{m}^2$ devices before and after SiN_x passivation for devices built on the HR-Si substrate. The static output characteristics were measured for the range $V_{DS} = [0 \text{ to } 8] \text{ V}$ with $V_{GS} = [0 \text{ to } -4] \text{ V}$. The devices show similar output I - V curves for both substrates, and a detailed comparison of I - V characteristics was given in [6]. As expected, the drain saturation current increased after passivation: the drain current at $V_{GS} = 0 \text{ V}$ increased from 425 mA/mm (500 mA/mm) to 545 mA/mm (590 mA/mm) on the HR-Si (sapphire) substrate. Figure 2 shows the transconductance characteristics before and after passivation for both substrates. We note that the threshold voltage shift toward more negative value following passivation. This may be due to an increase of sheet carrier concentration, but the phenomenon was not investigated in more depth. Peak DC extrinsic transconductances of 195 and 155 mS/mm were obtained for passivated devices on HR-Si and sapphire substrates, respectively. Devices on HR-Si show a higher transconductance due to the thinner (Al,Ga)N barrier layer (18.5 nm on HR-Si versus 25 nm on sapphire). The dc transconductance values indeed scale roughly with the nominal barrier thicknesses, and the same ratio roughly holds for the values extracted from RF measurements. Devices built on sapphire showed current collapse-related instabilities before they were passivated by a 100 nm thick SiN film deposition, as shown in the transconductance plot of Fig. 2(b). The gate diode leakage current on the passivated devices of Figs 1 and 2 was measured at the level of 7.6 and 36 $\mu\text{A/mm}$ at $V_G = -7 \text{ V}$ for the HEMTs on HR-Si and sapphire, respectively. The lower gate leakage on HR-Si is attributable to the low screw dislocation densities ($\sim 10^7/\text{cm}^2$) achieved by Nitronex on their GaN-on-Si layers (see www.nitronex.com more information). The lower gate diode leakage achieved in our GaN on HR-Si HEMTs translates into better I_{ON}/I_{OFF} ratios, as reported in [6].

RF measurements were performed from DC to 40 GHz with an HP8510 vector network analyzer using an off-wafer calibration standard and an LRRM calibration. The effects of probing pads were de-embedded using open and short patterns. Figure 3 characterizes the transistor microwave performance of devices on HR-Si and sapphire substrate for bias points corresponding to the maximum transconductance with $V_{DS} = 6 \text{ V}$. Although the devices on both substrates display quite similar DC characteristics, they react very

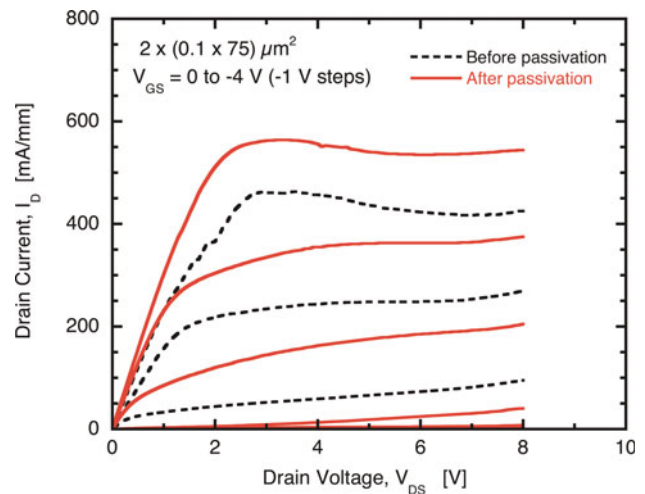


Fig. 1. Output characteristics of AlGaIn/GaN HEMTs before and after passivation on HR-Si substrate. Devices built on sapphire show nearly identical characteristics and are therefore not shown here since detailed comparison of their I - V characteristics is given in [6].

differently in terms of microwave performance. A -20 dB/dec extrapolation of $|h_{21}|^2$ and of Mason's maximum unilateral gain U yields $f_T = 49/56 \text{ GHz}$ and $f_{MAX} = 90/108 \text{ GHz}$ before and after passivation for the devices on HR-Si: the passivation therefore *markedly enhances* the RF performance on HR-Si. For devices on sapphire, the f_T and f_{MAX} decrease from 57 to 54 GHz, and from 102 to 77 GHz, following passivation.

It may also be of interest to consider at the raw (or extrinsic) device performance with pad effects included. For the devices on HR-Si the pre-de-embedding cutoff frequencies are $f_{T,E} = 38/46 \text{ GHz}$ and $f_{MAX,E} = 73/88 \text{ GHz}$ before and after passivation, indicating that the f_{MAX}/f_T ratio is essentially unaffected by the de-embedding process, thus contradicting the unfortunately too commonly held prejudice that GaN-on-Si devices necessarily suffer from conductive parasitic layers near the buffer/substrate interface. The parasitic buffer conduction can be satisfactorily addressed by optimizing growth conditions, as demonstrated here again on wafers from Nitronex. This view is strongly supported by our measurements of a CPW loss of only 0.82 dB/mm at 110 GHz for transmission lines built on HR-Si [6]. For devices built on sapphire, the pre-de-embedding cutoff frequencies are $f_{T,E} = 43/44 \text{ GHz}$ and $f_{MAX,E} = 81/63 \text{ GHz}$ before and after passivation. The role of passivation on the device RF performance is not straightforward when it comes to AlGaIn/GaN HEMTs: an increase [7] as well as a decrease [8] of f_T and f_{MAX} after passivation have been reported by different groups. The present results provide additional food for thought since devices undergoing nominally identical process steps in the same laboratory show dramatically different behaviors, despite the resemblance in the initial epitaxial layer stacks. Clearly then, the area of passivation effects in AlGaIn/GaN HEMTs is far from exhausted and much remains to be clarified.

Table 1 shows the difference in the small-signal parameters extracted from S-parameter measurements before and after passivation on both substrates. The ratio of $g_m/2\pi(C_{GS} + C_{GD})$ extracted from microwave measurements is in good agreement with the f_T values obtained in Fig. 3. Our results

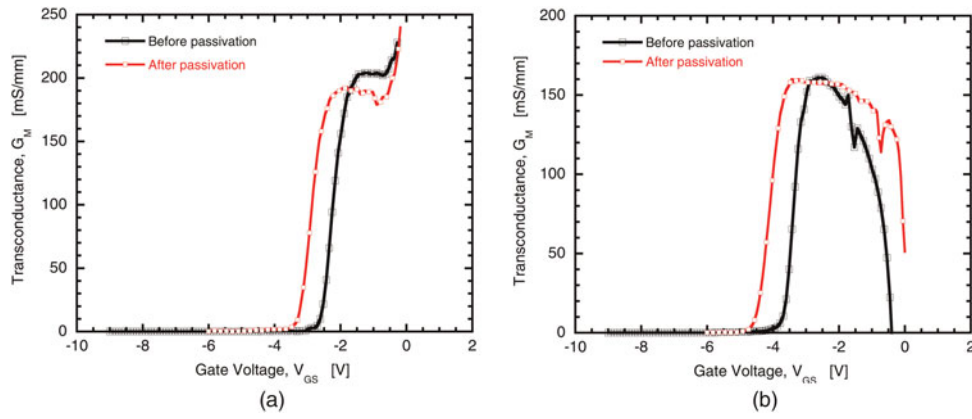


Fig. 2. Transconductance characteristics of AlGaIn/GaN HEMTs before and after passivation: (a) on HR-Si substrate, and (b) Sapphire substrate. The unpassivated device on sapphire suffers current collapse which causes a drop of transconductance near $V_{GS} = 0$ V. Passivation largely alleviates the current collapse on the devices built on sapphire.

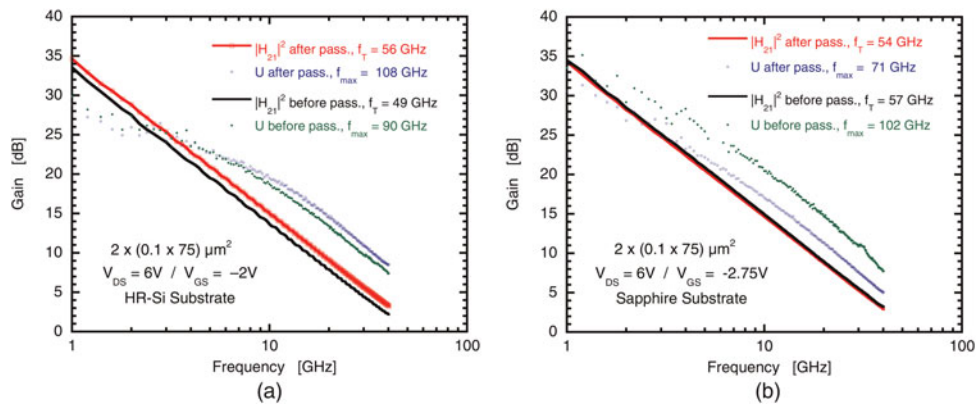


Fig. 3. Microwave performance of AlGaIn/GaN HEMTs before and after passivation, with pad effects removed: (a) on the HR-Si substrate, and (b) on the Sapphire substrate.

show that the SiN_x passivation has higher impact on the parasitic capacitance (such as C_{GS} and C_{GD}) for the GaN-on-sapphire devices than that on HR-Si. It should be mentioned that the passivated HEMTs built on HR-Si in fact feature a higher f_{MAX}/f_T ratio compared to the passivated devices on sapphire, and that the higher f_{MAX} can be traced to the lower microwave output conductance g_{DS} on the HR-Si substrate [6].

In order to produce a high-gain millimeter-wave power amplifier featuring a high reliability, it is important to simultaneously achieve high transistor cutoff frequencies f_T and f_{MAX} and high breakdown voltages. GaN HEMTs have the potential to meet this requirement because the high electron velocities achieved under high electric fields can be combined with high breakdown voltage values achieved, thanks to the wide energy gaps of the materials involved. Although very high $f_T \times BV$ products were reported on sapphire and SiC [9], there is a scarcity of reported results for GaN-on-silicon

device. Figure 4 characterizes the transistor microwave performance of devices on HR-Si with source-drain distance of $4 \mu\text{m}$: these devices were fabricated with a $0.1 \mu\text{m}$ gate centered in the source-drain space. A -20 dB/dec extrapolation of $|h_{21}|^2$ and of Mason's maximum unilateral gain U yields $f_T = 43 \text{ GHz}$ and $f_{MAX} = 77 \text{ GHz}$. Figure 5 shows the OFF-state breakdown voltage characterization of $BV_{DS} = 110 \text{ V}$ and $BV_{GD} = 130 \text{ V}$, as determined by the drain current injection technique of [10]. The $f_T \times BV$ products reach values as high as 5.6 THz-V , and 10 THz-V when it comes to $f_{MAX} \times BV$. Still higher $f_{T,MAX} \times BV$ products could be achieved by positioning the gate closer to the source contact.

Transistors featuring high-cutoff frequencies and large breakdown voltages are not only attractive for high-efficiency high-power amplifier applications (which demand minimal dispersion non-idealities), but also in wideband highly rugged low-noise amplifiers which can be built without

Table 1. Device de-embedded parameters dependence on substrate type and passivation film.

Substrate	Passivation	f_T (GHz)	f_{MAX} (GHz)	f_{MAX}/f_T	$g_{m,RF}$ (mS)	C_{GS} (fF)	C_{GD} (fF)	C_{DS} (fF)	G_{DS} (mS)
HR-Si	Before	48.9	90	1.84	20.3	56.2	10.6	18.6	2.4
	After	56	109	1.94	26.8	61.5	14.7	22.1	3.3
Sapphire	Before	57	102	1.79	17.5	41.9	8.4	22.7	3.0
	After	54	71	1.31	22.5	52.6	14.8	20.4	4.6

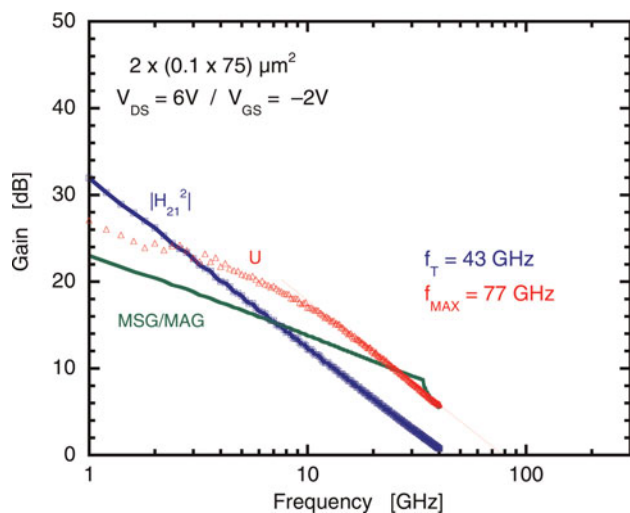


Fig. 4. Microwave performance measured at $V_{DS} = 6$ V and $V_{GS} = -2$ V for $2 \times (0.1 \times 75) \mu\text{m}^2$ HEMT. Extrapolation at -20 dB/dec yields $f_T = 43$ GHz and $f_{MAX} = 77$ GHz. Pads effects de-embedded.

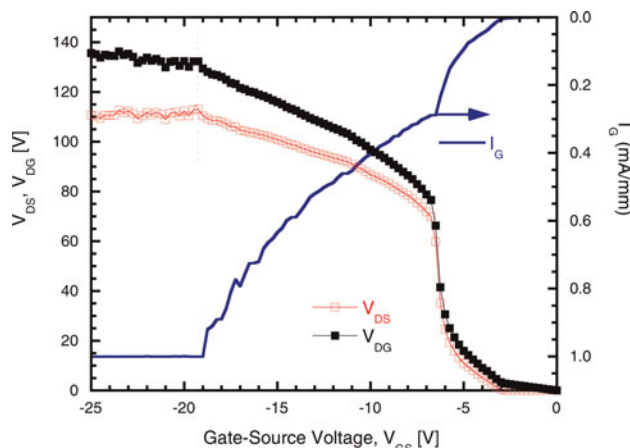


Fig. 5. Three terminal off-state breakdown characteristics of the conventional HEMT using the drain-current injection technique [10]. The drain current is fixed at 1 mA/mm and V_{GS} is swept from 0 to -25 V (same device as Fig. 4).

input protection circuitry thanks to the low-noise figures achievable at X- and K-band frequencies [3]. In this context, it becomes interesting to push AlGaIn/GaN HEMTs to higher frequencies of operation. This is also of interest for us at ETHZ.

III. EXTENSION TO HIGHER FREQUENCIES

Perhaps because of the unavailability of truly semi-insulating silicon substrates, comparatively little work has been performed prior to 2008 to determine whether or not AlGaIn/GaN HEMTs on silicon offer a viable technological solution for the realization of mm-wave transistors with interesting properties. We have first reported very good cutoff frequencies with f_T of 75 GHz and noise figures interesting properties in $0.1 \mu\text{m}$ HEMTs grown on HR-Si [3]. With increasing process maturity, we eventually achieved HEMTs with an f_T of 90 GHz [4]. On improved epitaxial layers featuring an

electron mobility of $\sim 1500 \text{ cm}^2/\text{Vs}$ from Nitronex Corporation, we now fabricate fully passivated $(2 \times 75) \mu\text{m}$ wide (Al,Ga)N/GaN HEMTs with 100 nm gate lengths and source-drain spacing L_{SD} of $1 \mu\text{m}$. These devices feature an $f_T = 104$ GHz which is the highest ever achieved for GaN-based HEMTs on silicon substrates, shown in Fig. 6. Although the bulk of our activities have so far focused on AlGaIn/GaN HEMTs on HR-Si because of an excellent supply relationship with Nitronex, our process also results in attractive performances when applied to GaN HEMTs on SiC: Fig. 7 shows that 100 nm gate transistors with f_T of 126 GHz have been realized at ETH-Zürich. As far as we know, these are the fastest GaN-based HEMTs so far produced in Europe. More recently, we have also demonstrated the realization of 100 nm gate AlInN/GaN HEMTs with $f_T = 144$ GHz and $f_{MAX} = 145$ GHz using epitaxial layers

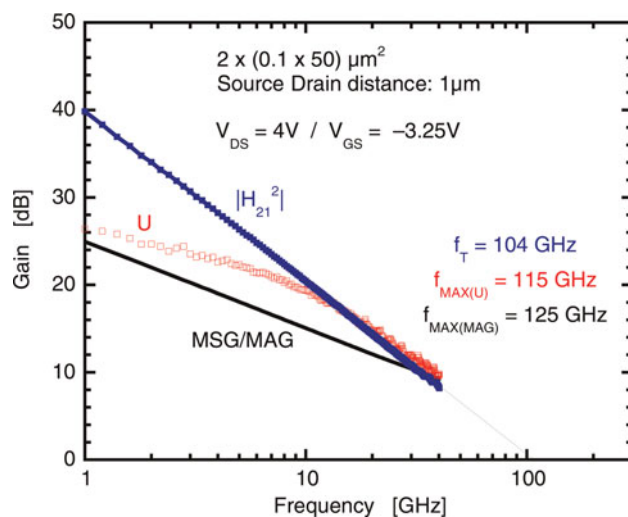


Fig. 6. Microwave performance measured at $V_{DS} = 4$ V and $V_{GS} = -3.25$ V for $2 \times (0.1 \times 50) \mu\text{m}^2$ HEMT on silicon substrate. Extrapolation at -20 dB/dec yields $f_T = 104$ GHz and $f_{MAX(U)} = 115$ GHz and $f_{MAX(MAG)} = 125$ GHz. Pad effects de-embedded.

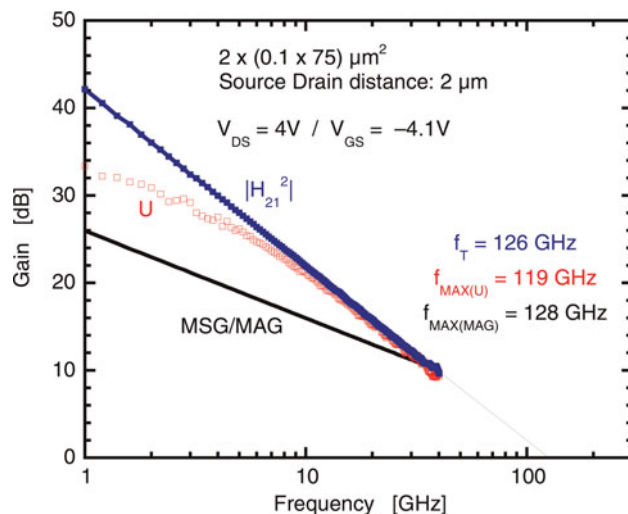


Fig. 7. Microwave performance measured at $V_{DS} = 4$ V and $V_{GS} = -4.1$ V for $2 \times (0.1 \times 75) \mu\text{m}^2$ HEMT on SiC substrate. Extrapolation at -20 dB/dec yields $f_T = 126$ GHz and $f_{MAX(U)} = 119$ GHz and $f_{MAX(MAG)} = 128$ GHz. Pad effects de-embedded.

grown on SiC at EPFL, thus setting a new record for AlInN/GaN and closing the cutoff frequency gap between AlInN/GaN and AlGaIn/GaN HEMTs [11].

IV. SUMMARY

Since being established in 2006, the Millimeter-Wave Electronics Group at ETH-Zürich has developed high-performance AlGaIn/GaN HEMT processes enabling the demonstration of surprisingly good RF and noise performances for material grown on HR-Si (111) substrates, therefore narrowing the performance gap between devices grown on silicon and on insulating substrates such as sapphire and SiC. The ETHZ AlGaIn/GaN HEMT process architecture is not limited to HR-Si substrates, as it also provides excellent device performances for materials grown on SiC substrates, as exemplified by the realization of 100 nm gate HEMTs exhibiting cutoff frequencies of $f_T = 126$ GHz on SiC semi-insulating substrates. Work is currently underway to exploit these device performances by establishing a power MMIC process at ETH-Zürich.

More recently, our Group set the record for the highest-speed AlInN/GaN HEMT ever reported with an $f_T = 102$ GHz using EPFL material grown on HR-Si and demonstrated a reasonable output power of 2.5 W/mm at 10 GHz in 100 nm gate transistors built in a 1 μ m source-drain space which only allowed low breakdown voltages which limited the output power level [5]. As of writing time, we have now established a new record for 100 nm gate AlInN/GaN HEMTs, again on EPFL material but this time grown on S.I. SiC to reach cutoff frequencies of $f_T = 144$ GHz, which matches the fastest achieved for thin-barrier AlGaIn/GaN devices of the same gatelength [11]. It is noteworthy that the fastest thin-barrier AlGaIn/GaN HEMTs use thin ~ 2 nm SiN passivation/gate dielectric films and also feature relatively leaky gates.

Although an increasing number of research workgroups worldwide have undertaken the development of nitride transistors for mm-wave applications, few if any have shown activities in this direction in Europe. This is, however, a role that naturally fits the interests and expertise of our Group, regardless of substrate type.

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Diego Marti was born in Zürich, Switzerland. He received the M.Sc. in Electrical Engineering and Information Technology from the Federal Institute of Technology (ETH), Zürich, Switzerland, in 2009. His studies focused on circuit design and optoelectronics design and processing. For his Masters thesis, he designed and

implemented wideband distributed amplifiers in a hybrid

microstrip environment using 100 nm gate GaN HEMTs grown on high-resistivity silicon. Diego Marti started his Ph.D. work in 2009 at ETH and is working in the field of GaN HEMTs devices and circuit design and fabrication.



Stefano Tirelli was born in Reggio Emilia, Italy. He received the B.S. degree in Physics from University of Pisa, Italy in 2003, with a thesis carried out at California Institute of Technology, USA. He received his M.S. degree in Matter Physics from University of Pisa in 2008. His Masters' thesis, carried out at NEST Laboratory

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Andreas R. Alt was born in Munich, Germany. He received his B.S. degree in Electrical Engineering in 2004 and the Diploma (Masters) degree in Electrical Engineering in 2006 from Technical University of Munich (TUM), Germany. In 2006 he began his Ph.D. degree in the

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Hansruedi Benedickter was born in Zug, Switzerland. He received the Diploma degree in Electrical Engineering from the Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, in 1976. He has been a Research Assistant and a Senior Research Associate at the Microwave Laboratory, Swiss Federal Institute of Technology, and, since 1987, at the Laboratory for Electromagnetic Fields and Microwave

Electronics. His main research interests are microwave, millimeter-wave, and on-wafer measurement techniques.



Colombo R. Bolognesi was born in St-Lambert QC, Canada. He earned the B.Eng. from McGill University (Montréal QC) in 1987, the M.Eng. from Carleton University (Ottawa ON) in 1989, and the Ph.D. from the University of California, Santa Barbara (UCSB) in 1993, all in Electrical Engineering. His doctoral dissertation

dealt with the growth, fabrication, and physics of InAs/AlSb HFETs and led to the first high-speed InAs/AlSb HFET high-yield process. In 1994, he joined Northern Telecom's Semiconductor Components Group in Ottawa, as a BiCMOS process integration engineer responsible for high-performance submicron polysilicon emitter BJT's with selectively implanted pedestal collectors. In 1995, he joined the Engineering Science and Physics Departments at Simon Fraser University to launch and direct SFU's Compound Semiconductor Device Fabrication Laboratory (CSDL). In 2001, his group demonstrated the first bipolar transistors in any material system with balanced f_T and f_{MAX} cutoff frequencies simultaneously exceeding 300 GHz with a 6 V breakdown voltage, by exploiting the new InP/GaAsSb type-II heterojunction system. In 2006, he took up the Chair of Terahertz Electronics at the Institut für Feldtheorie und Höchstfrequenztechnik (IfH) at the Swiss Federal Institute of Technology in Zürich (ETH-Zürich). In 2010, the THz Electronics Group was renamed Millimeter-Wave Electronics and split from the IfH to stand as an independent Chair at ETH. Professor Bolognesi's research continues to target the development of high-speed devices (HBTs, HEMTs) based on InP/GaAsSb/GaInAs and AlGaIn/GaInN to extend their application toward higher frequencies. Among others, he and his team earned the IEEE 1999 GaAs IC Symposium Best Paper Award, and he was the co-recipient of the New Frontiers in Research Award from the Science Council of British Columbia in 2001. He serves/served on the Technical Program, Executive and/or International Steering Committees of several IEEE sponsored conferences such as the Device Research Conference (DRC'01 and '02), the Int. Electron Device Meeting (IEDM'01, '02, and '03 as the QEC Chair), and the Indium Phosphide and Related Materials Conference (IPRM'03, '07, '08, '09) as well as the Int. Symposium on Compound Semiconductors (ISCS'07, '08, '09).